Optical-IR Spectral Energy Distribution of the Proto-Galaxy Candidate MS1512-cB58

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ABSTRACT

The spectral energy distribution of the proto-galaxy candidate MS1512-cB58 at $z = 2.72$ discovered by Yee et al. (1996) is presented. Photometry in seven bands ranging from g to K' (1300–6000 Å rest wavelength) are fitted with population synthesis models from Bruzual & Charlot (1993). The data confirm a very young age for this galaxy, in agreement with ages estimated from preliminary C IV λ1550 P-Cygni profile modeling. Single-burst models with ages greater than about 20 Myr can be discarded at the 99% confidence level, and continuous star formation models with ages greater than about 35 Myr can be discarded at the 95% confidence level. The spectral energy distribution is most consistent with a continuous star formation model of about 10–20 Myr, with reddening of $E(B-V) \sim 0.3$. No evidence for an older population of stars is seen, but the possibility of an older population with as much as

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90% of the galaxy mass cannot be ruled out. We discuss the possible ramifications of a non-standard IMF and gravitational lensing on the galaxy's age and mass.

Subject headings: galaxies: formation — galaxies: starburst — galaxies: photometry

1. INTRODUCTION

The identification of the high-redshift precursors of normal present-epoch galaxies, and specifically a galaxy in its first episode of star formation, has long been an elusive goal (e.g., Partridge & Peebles 1967). In past decades, a wide variety of models have been suggested and techniques attempted to identify such proto-galaxies (see Koo 1986 and Pritchet 1994 for reviews). The proto-galaxy candidate serendipitously discovered by Yee et al. (1996; hereafter Paper I) may offer an excellent chance to study a very young galaxy in detail. The $V = 20.64$ galaxy, designated as MS1512-cB58, (hereafter, cB58), lies in the field of the $z = 0.37$ galaxy cluster MS1512+36, which was observed as part of the Canadian Network for Observational Cosmology (CNOC) cluster redshift survey (see Yee, Ellingson & Carlberg 1996). The galaxy was found to have $z = 2.72$ by identification of about a dozen strong absorption lines indicative of young stars. Optical colors— Gunn g, V, Gunn r and Johnson I— indicated that the stellar population of this galaxy is less than 400 Myr old. However, the uncertain extinction correction made it difficult to constrain the galaxy age to better than a range of 10–400 Myr. P-Cygni profiles in the C IV λ1550 absorption lines suggested that the rest UV flux is dominated by a population as young as 10 Myr old.

In this paper we present data in three additional photometric bands in the infrared: J, H and K'. These data allow stronger limits to be placed on both the extinction and the age of the stellar populations in this galaxy. We also explore the possibility of underlying older populations and discuss briefly the effects of non-standard initial mass functions and gravitational lensing on our conclusions.

2. Observations and Data

J and K' images were obtained on 1995 Sep 28 UT at the NASA Infrared-Telescope Facility (IRTF) with the NSFCAM imager, which contains a 256x256 InSb array (Shure & Rayner 1993). The plate scale was $0.30''$ per pixel. The data were obtained under photometric conditions with seeing $0.8 - 0.9''$. For K', a 25 point grid with integration times of 15 seconds, 4 co-adds each, was used, resulting in a total integration time of 1500 seconds. For J, a 15 point grid was used with 20 second exposures, 3 co-adds each, resulting in 900 seconds of integration. The UKIRT Faint Standards #28 and 26 (Casali & Hawarden 1992) were observed for calibration just before and just after the galaxy observations. The data were reduced using standard techniques.

Images in the H band were obtained at the CFHT 3.6m using the Redeye-Wide Infrared Camera with a 256×256 pixel NICMOS3 HgCdTe array on the night of 1995 Dec 30 UT, under photometric skies. The pixel size of the detector is $0.5''$ per pixel. Six sets of 9 dithered frames of 35 seconds exposure were obtained, providing a total integration time of 1890 seconds. The photometry was calibrated using observations of the UKIRT Faint Standard Star #23 (Casali & Hawarden 1992) taken before and after the galaxy observations.

Photometry in the optical bands of g, V, r, and I is taken from Paper I. The photometry for the near IR observations was derived in the same way as the optical data (see Paper I), using an aperture of $2.2''$ diameter for the object and $9''$ for the outer diameter of the sky aperture. The $2.2''$ aperture photometry is then corrected to the "total" magnitude at an aperture equivalent to the V isophote of 24.1 mag arcsec^{-2}, assuming zero color gradients. The photometric data along with their uncertainties are listed in Table 1. Also listed are the magnitudes in the AB system, where corrections for the IR photometry were based on the 0 mag fluxes from Wamsteker (1981).

3. Discussion

3.1. Spectral Energy Distribution Models

In order to test the calibration of photometry gathered from several different sources, the spectral energy distributions (SEDs) of galaxies of known redshift near cB58 are first examined. Figure 1 plots the data for the cD galaxy of the cluster and a bright companion galaxy located $6''$ W and $18''$ S of the cD (designated #100983 in the CNOC catalog, Abraham et al. 1996). The cD galaxy has a spectrum of an old population of stars but with strong [OII] emission, and possibly a somewhat blue continuum– both presumably associated with the cooling flow detected in this cluster (Donahue, Stocke & Gioia 1992). Figure 1 also shows GISSEL spectral synthesis models from Bruzual & Charlot (1993). Both models are for a 13 Gyr old single burst (coeval) population with a Salpeter initial mass function (IMF). This standard IMF has an upper mass cutoff $125M_\odot$, and a lower mass cutoff of $0.1M_\odot$. The models fit the data reasonably well, indicating that there are probably no gross inconsistencies in the calibration of the SEDs. Note that the model is slightly lower than the cD data bluewards of the 4000 Å break, as expected.

In Paper I, it was pointed out that interpreting the age of a stellar population from rest UV data is complicated by dust extinction. The SED was modeled assuming extinction occurs in the rest frame, and a slightly modified version of the average LMC curve from Fitzpatrick (1986) was used. Both here and in Paper I, the 2175Å hump in the LMC extinction was interpolated over, based on the fact that there is no evidence for the expected prominent dip due to this feature in the optical spectroscopy data. Note that many local star burst galaxies also do not show this bump in the extinction in their IUE spectra (Kinney et al. 1993). An extinction law derived from UV observations of starburst galaxies (Calzetti et al. 1994) was also tested and found to yield qualitatively the same results. The extinction in this case has a significantly grayer slope than

that from the LMC, and hence requires a larger amount of extinction to provide enough reddening to fit the SED. This in turn will increase the already high rest optical luminosity of this galaxy. Hence, the more conservative LMC law is adopted.

Three single burst GISSEL models were presented in Paper I to illustrate the range of parameters allowed by the optical data: 400 Myr old with no extinction, 200 Myr old with the equivalent of $E(B-V)=0.18$, and 10 Myr old with $E(B-V)=0.3$. The oldest single burst model possible was 400 Myr, and that the maximum dust extinction possible was about $E(B-V)\sim 0.4$, since the intrinsic spectrum would become bluer than the hottest stars if more dust is assumed. In Figure 2, these three models are plotted again, this time including the IR data. The spectral range is now from 1300–6000 Å rest. Each model is normalized to match the optical data, as in Paper I, and assumes a Salpeter IMF with the mass limits noted above. It is clear that the only model which comes close to fitting the new IR data is the youngest model, of a 10 Myr old single burst and $E(B-V)=0.3$. The older models clearly predict too much IR flux in the J through K' bands to match the data. No single burst model fits the data within the 95% confidence level and we can conservatively rule out all models older than 20 Myr at the 99% confidence level. Note that the J and H bands straddle the 4000 Å and Balmer breaks and can be used alone as an age indicator which is relatively insensitive to extinction. The blue slope of the spectrum in this region clearly indicates that the SED is dominated by a young population.

Continuous star formation models provide a more physically plausible scenario. For these models, the rest UV flux is always dominated by very young stars, and in Paper I it was found that no age discrimination was possible using just the optical data. However, over time it is expected that the observed IR flux will increase. Figure 3 shows continuous star formation models of ages 5, 10, 50, and 500 Myr, assuming a Salpeter IMF. Here the data have been corrected for extinction equivalent to $E(B-V)=0.3$ to match the observed optical data. The IR data clearly favor the 10 Myr continuous star formation model, and renormalization of the models relative to the data also provides good fits to ages as high as 20 Myr. Models older than about 35 Myr are ruled out at the 95% confidence level. Both of these estimates are consistent with preliminary modeling in Paper I of the P-Cygni profile of the C IV λ1550 absorption line, which suggests a lower limit of 10 Myr for a continuous star formation scenario.

3.2. Limits On a Possible Older Population

The IR data show that the observed episode of star formation is relatively young, but does it represent the very first incidence of star formation in this galaxy? Limits on the size of an underlying older population can be estimated from these data but are relatively broad, because even at K' (rest V), the continuum light is still dominated by the young population. The SED is modeled as two episodes of star formation: the observed burst, which is modeled as a 10 Myr old continuous episode of star formation (referred to hereafter as the 10Myr model), and an older population, which is modeled as a single burst model with varying age and mass relative to the

10Myr model. Both models assume the standard Salpeter IMF. For all combinations, the best fits to the data suggest no contribution from an older population. Upper limits at the 95% confidence level were determined for the fraction of total stellar mass in the older population. Note that as the population ages, its SED differs more in shape from the 10Myr model. However, the rapid fading of the single burst SED with age makes it possible to hide a slightly increasing mass fraction underneath the younger distribution. Thus, the constraints on the mass fraction of the older population are a weak function of its age, ranging from 83% of the total stellar mass for a 100 Myr old population, to 90% for a 2 Gyr old population. Figure 3 also shows an example of a 1 Gyr old single burst combined with the 10Myr model, where the older population has a mass equal to 85% of the combined stellar mass. This model can be ruled out at the 95% confidence level. The high redshift of cB58 indicates an upper limit on the age of any older population of about 2 Gyr, depending on the cosmological parameters assumed. Thus, it is possible to conclude that there is no evidence for an older stellar population, and most conservatively that cB58 has formed at least 10% of its stars within the previous 10-20 Myr.

3.3. Total Stellar Mass and Star Formation Rates

A lower limit on the total stellar mass can be estimated by noting that the K' band is approximately equivalent to rest V at $z = 2.72$. The K'_{AB} magnitude of 19.61 therefore implies an extinction-corrected rest V absolute magnitude of –27.94 mag (H_0 = 75 km s^{-1} Mpc^{-1}, q_0=0.1, A$_V$=0.93 mag). Assuming a 10 Myr old single burst model with no underlying older population, the galaxy is expected to fade approximately 6 mag over the next 10 Gyr (the lookback time to $z = 2.72$). Note that after 10 Gyr the differences between an instantaneous burst and just 10 Myr of continuous star formation would be extremely subtle, so the choice of the initial model is not important. Thus, the observed star formation in cB58 would be the precursor of a galaxy at least as bright as –21.9 mag, or about 2.7 L^*. Any subsequent star formation or the presence of an additional older population would serve to make its present-epoch luminosity even greater, which argues against a significant older population.

The high luminosity of cB58 implies prodigious rates of star formation. Paper I estimates star formation rates of 4700 M$_\odot$ yr^{-1} based on the 1500Å flux and continuous star formation models by Leitherer, Robert, & Heckman (1995). The homogeneous appearance of the galaxy suggests that this intense star formation is not localized, but must be occurring across the 30 kpc visible galaxy on close to dynamical timescales. At this rate, a L^* galaxy would be created in a few 10's of Myr. It is not clear whether such a short, intense phase of star formation over the entire galaxy is dynamically possible. It is also unclear whether the implied supernova rates would allow the galaxy to retain any gas for further star formation, or whether supernova-driven winds would quickly strip the galaxy of its interstellar medium.

The implied star formation rates and total stellar masses are highly dependent on the initial mass function assumed. Variations in the upper mass cutoff do not affect the age of the young

population, although they can change the star formation rate by up to a factor of about 5 (Paper I, Leitherer et al. 1995). Lower-mass cutoffs as high as $10 M_\odot$ have been predicted for regions of intense star formation (e.g. Scalo 1990). Evidence for such a cutoff has been mixed for nearby star forming galaxies, with some galaxies showing near-normal IMFs (e.g. Hunter et al. 1995) and others showing indications of a lower-mass cutoff (e.g. Rieke et al. 1993). The available GISSEL models only allow fits to models up to a fairly small $2.5 M_\odot$ cutoff. Such a low-mass cutoff provides a slightly poorer fit to the observed SED, but is not significantly worse and cannot be ruled out. More extreme cutoffs would lower the IR flux of the models, but since massive stars contribute most of the SED, even into the IR, the data are not sufficient to discern between a slightly younger population and a more extreme cutoff. Thus, a lower mass cutoff at masses greater than $2.5 M_\odot$ might allow a somewhat older age for the galaxy. A similar conclusion would be reached for a flatter IMF. A low-mass cutoff would of course also significantly lower the inferred star formation rate and total stellar mass for cB58. Episodes of intense star formation with an extreme low-mass cutoff would temporarily increase the galaxy's luminosity without adding significantly to its stellar mass. In this case, the example of cB58 would not add greatly to our understanding of the origin of present-day stellar populations in normal galaxies.

The object is clearly extremely different from many other proto-galaxy candidates in its stellar SED and high luminosity. In comparison with the galaxies at $z \sim 3$ studied by Steidel et al. (1996), cB58 is about 40 times brighter (assuming the same extinction), and may have slightly higher equivalent width stellar absorption lines. An important difference is that the $(R-K)_{AB}$ color of cB58 is 0.8 mag, bluer than the average value of 1.3 mag for the Steidel et al. sample. This may indicate more dust in the fainter galaxies or that they have an older stellar population on average. If the color difference is from dust, an additional $E(B-V)$ of 0.1–0.2 (for the LMC and Calzetti et al. extinction laws, respectively) in the Steidel et al. galaxies is necessary to explain the color difference. In this case, cB58 would be still a factor of 20 brighter in the rest V band. Ages for the Steidel et al. galaxies of greater than 100 Myr would also explain the color difference. If continuous star formation for 10 and 100 Myr is assumed for cB58 and the Steidel et al. sample, respectively, then cB58 is undergoing star formation at a rate of about 40–100 times that of the Steidel et al. sample.

An important possibility to consider is that the high luminosity of cB58 is in part due to gravitational lensing from the foreground cluster MS1512+36. The galaxy is located only $6''$ from the cluster cD and is a very strong candidate for lensing. However, the image is resolved on both major and minor axes, appears quite homogeneous and its surface brightness profile can even be fit with an exponential disk model (Paper I). Williams & Lewis (1996) have modeled the possible lensing of cB58, assuming a subcritical cluster potential. They found that if the cluster mass of E1512+36 is well represented by its velocity dispersion (690 km sec^{-1}; Carlberg et al. 1996), and Abell richness (class 0; Abraham et al. 1996), then the lensing magnification is at most about 2 magnitudes. However, if the cluster mass is a factor of 2 larger, and assuming a specific geometry, then up to a factor of 40 magnification can be obtained without obvious distortion in

the ground-based images. This factor of 2 in mass seems difficult to come by, as it requires a 3–σ error on the velocity dispersion determination (Carlberg et al. 1996). Williams & Lewis note that the X-ray luminosity of the cluster is higher than the velocity dispersion suggests, but the presence of a cooling flow in the cluster will tend to increase the observed X-ray luminosity. Furthermore, the X-ray luminosity and the measured velocity dispersion of MS1512+36 are well within the scatter of correlation of these quantities found by Edge & Stewart (1991). Thus there seems to be only a small possibility that this object is highly lensed, although magnification by factors of a few would not be surprising.

Unless the gravitational lensing magnification is much larger than the cluster dynamics and image morphology suggest, the star formation rates in this galaxy are probably on the order of at least several hundred to a thousand solar masses per year and are distributed fairly homogeneously across the entire galaxy. Clearly such rates cannot persist for long, and thus we expect a subsequent decrease in star formation and luminosity of this galaxy in future times. This initial high rate of star formation and later decline suggests that cB58 may be a precursor of a 1–3L^* early-type galaxy. If the lensing magnification is much larger, then the stellar mass of cB58 would be correspondingly smaller, but its young age and the fraction of stars in the observed 10–20 Myr old episode of star formation would be unchanged. In this case, cB58 may represent the initial stages of any of a wide variety of galaxy types.

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Fig. 1.— Optical-IR spectral energy distribution for a) the cluster cD at z=0.37 and b) a probable cluster galaxy. Wavelengths are rest wavelengths.

Fig. 2.— Comparison of single burst star formation models with the extinction-corrected spectral energy distribution. The three models represent (from top to bottom), a 10 Myr old single burst with $E(B-V) = 0.3$, a 200 Myr old burst with $E(B-V) = 0.18$ and a 400 Myr old burst with $E(B-V) = 0$. All models are scaled to match the optical data (1200–3000 Å rest) and the dashed lines connect the SED points with the same extinction correction. The 10 Myr model and data are shifted by +1 in the log for clarity.

Fig. 3.— Comparison of continuous star formation models with the observed SED. The data are corrected for extinction equivalent to $E(B-V) = 0.3$. The three solid lines represent (from bottom to top): 5, 10, 50 and 500 Myr old models. The dashed line is a combination the 10Myr model (15% by mass) and a 1 Gyr old single burst model (85% by mass). The models are scaled to match the optical data (1200–3000 Å rest).

Table 1. Photometry (3″ aperture)

Band	Central λ (Å)	Magnitude	$\pm$	AB Magnitude
g	4930	21.08	0.10	21.15
V	5500	20.64	0.12	20.64
r	6540	20.60	0.10	20.41
I	8060	19.92	0.12	20.35
J	12400	19.12	0.13	19.95
H	16000	18.42	0.10	19.82
K'	21400	17.83	0.12	19.61

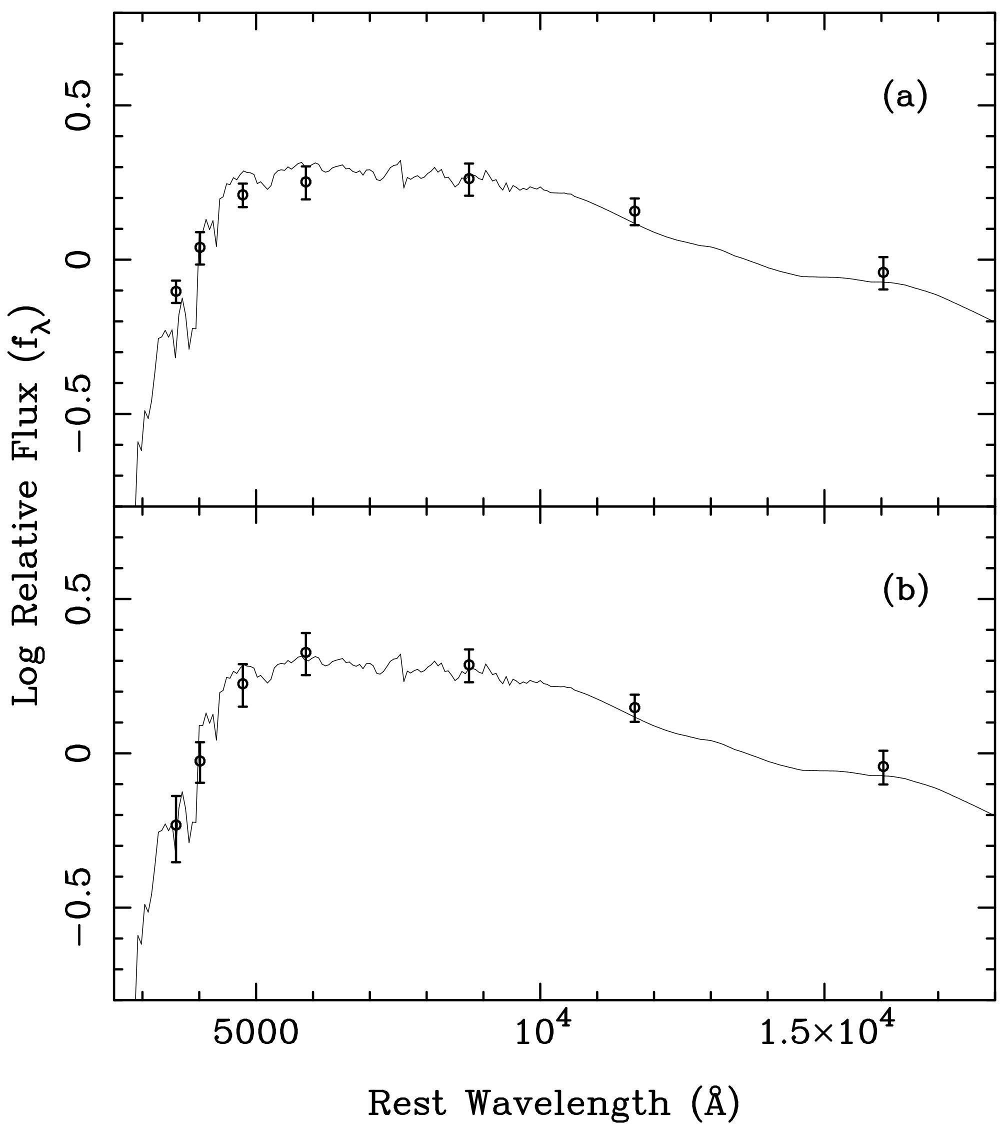
(a)
(b)
0.5
0
−0.5
Log Relative Flux (f_λ)
5000
10^4
1.5×10^4
Rest Wavelength (Å)

Fig. 1.—

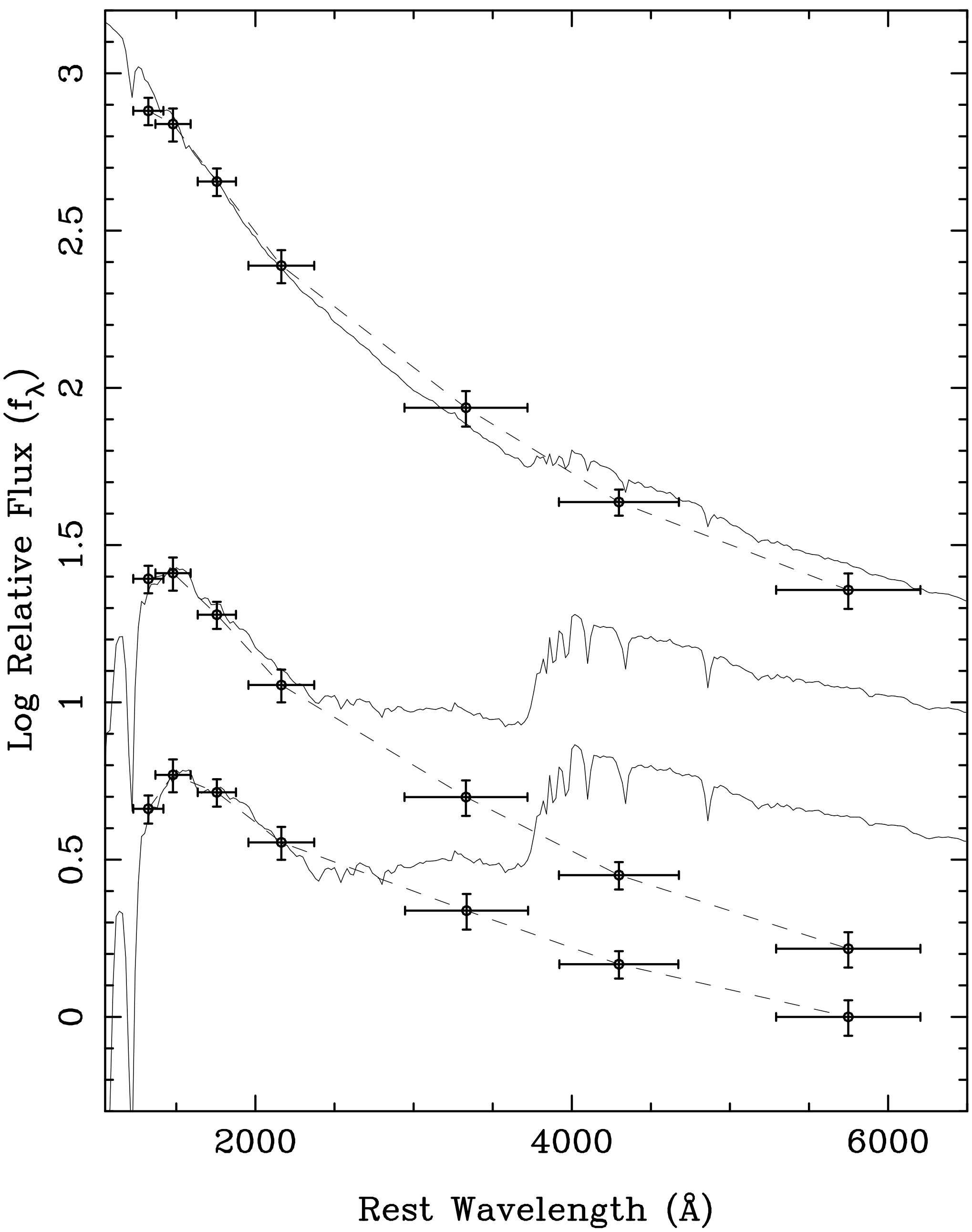
Log Relative Flux (f_λ)
Rest Wavelength (Å)
0
0.5
1
1.5
2
2.5
3
2000
4000
6000

Fig. 2.—

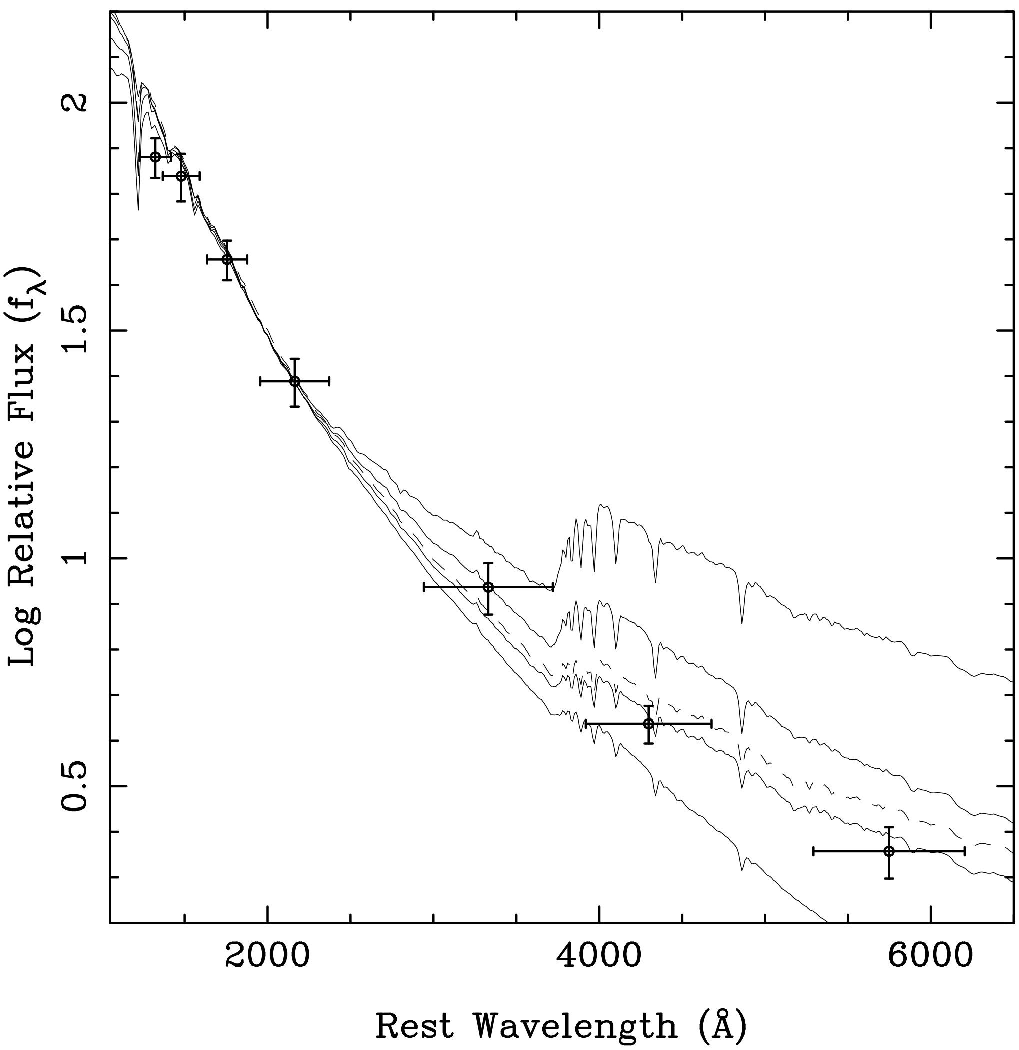
Log Relative Flux (f_λ)
Rest Wavelength (Å)
2
1.5
1
0.5
2000
4000
6000

Fig. 3.—